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SUMMARY OF RE-ENTRY PHYSICS RESEARCH PROGRAM ON TURBULENT WAKES

D. Heckman

CENTRE DE RECHERCHES POUR LA DEFENSE
DEFENCE RESEARCH ESTABLISHMENT
VALCARTIER

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(10) D./Heckman

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CENTRE DE RECHERCHES POUR LA DEFENSE
DEFENCE RESEARCH ESTABLISHMENT
VALCARTIER
Tel: (418) 844-4271

DN
403 445

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November/novembre 1973

RESUME

Ce rapport comprend surtout un catalogue de plus de 100 documents, Rapports, Notes techniques et Mémorandums, publiés au CRDV au cours d'un programme de recherche sur les sillages turbulents des projectiles hypersoniques, programme exécuté conjointement par le CRDV et l'ARPA au Centre de recherches pour la défense, Valcartier. (N C)

ABSTRACT

This report consists mainly of a catalogue of over 100 DREV reports, technical notes and memoranda issued during the course of the jointly sponsored DREV and ARPA research program on hypersonic turbulent wakes which was carried out at the Defence Research Establishment Valcartier during the years 1964-1972. (U)

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1.0 INTRODUCTION

For a period of almost eight years, extending from 1965 to 1972, the Defence Research Establishment Valcartier (DREV) and the Advanced Research Projects Agency (ARPA) have jointly sponsored a research program of experimental investigation of the behavior of the properties of turbulent wakes behind hypersonic projectiles. This research program was carried out mainly in the hypersonic ballistic range facilities of DREV. Of course, this was not the first occasion that cooperative Canadian and U.S. research was undertaken at DREV; in fact the interest in hypersonic research at DREV of the U.S Army Guided Missile Agency (ARGMA) (which became the Army Ordnance Missile Command (AOMC) and subsequently the Army Missile Command (AMC)) goes back to at least 1958.

The objectives of the joint turbulent wake research program were laid down in a work statement promulgated in early 1965. According to this statement the research effort was to emphasize the determination of the aerodynamic structure and dynamics of the base flow and wake behind blunt and slender models of typical reentry vehicles at speeds of around 16,000 feet/second and, wherever possible, direct probe techniques were to be used for obtaining the measurements.

In more detail, the aims of the research included making spatially resolved measurements of the mean mass density, velocity, temperature and charge density distributions in turbulent hypersonic wakes, and also measurements of the fluctuating properties of these variables. The designs or adaptations of the experimental equipment required to realize these objectives were carried out under the direction of DREV scientists, as were the actual measurements and the analyses of the experimental observations.

The progress of the program towards a successful conclusion was not without its difficult periods. In 1969, the wake measurements program had to be completely halted to permit a maximum effort to eliminate or minimize the effects of reflected shock waves in the ranges. Almost a whole year passed before a promising treatment was discovered, engineered and installed in the DREV ranges. Regrettably, because of budgetary and manpower restrictions, it was not possible to incorporate into the program a mass spectrometer experiment to measure species concentrations. Another difficult period occurred during the analysis and reporting phase of the program. In this instance, a system of signal recording and processing, which had been adequate and in some aspects highly advantageous for the development of the experimental techniques, broke down under the onslaught of masses of results from a firing program designed for production of data. Fortunately, the cooperation of both DREV and ARPA made possible a time extension of the program for analysis and reporting purposes. This time extension, combined with the strenuous efforts of individual DREV scientists, has permitted the proper reporting of most of the results of the experimental investigations conducted under the wake research program.

This document will serve as a final report on the technical activity at DREV which was related to the joint DREV-ARPA research program on the turbulent wakes of hypersonic projectiles.

2.0 THE AIMS OF THE PRESENT DOCUMENT

Generally speaking, the turbulent wake research program undertaken at DREV has been successful. The mean mass density, velocity, temperature and charge density behaviors in hypersonic sphere wakes have been very well mapped and useful results have been obtained concerning the behavior of velocity fluctuations, charge density fluctuations and wake intermittency. Considerable information has also been obtained on the velocity, mass density and temperature behavior in hypersonic cone wakes, even though measurements in cone wakes are considerably more difficult than in sphere wakes.

From a purely scientific viewpoint, the most desirable and possibly the only adequate summation of the wake program would take the form of a comprehensive paper which synthesized all the DREV experimental data, compared them with existing or new theoretical work and drew new conclusions concerning various theoretical models of the physical processes in the wake. In fact, such a summation could not be written at DREV because by deliberate design the entire effort here was wholly committed to the experimental investigation of hypersonic turbulent wakes, with any matching theoretical work being left for others to carry out elsewhere. While this arrangement may seem unfortunate to some, it must be realized that the effort at DREV was only one fragment of a very large tableau of research being undertaken into various aspects of re-entry physics.

Accordingly the aims of this document are rather modest compared to those of a comprehensive paper. What this report attempts is to briefly catalogue the individual components of the total documentation of the wake research program undertaken at DREV. All of the details of the various experiments and their significant findings are left to individual reports. This approach is feasible because the final reports dealing with particular measurements of the behavior of a certain variable in the wake have been prepared as self-contained entities; in each case, they describe the experimental techniques employed to make the measurements, the results obtained and the approximate statistical precision of the results. Where possible, comparison is made of the DREV results with the experimental data obtained at other laboratories. Frequently, because of the paucity of results obtained under similar conditions at other laboratories, no realistic comparison was possible. Occasionally, the best data available for possible comparison was that provided by observations made with one of the other experimental techniques employed at DREV.

3.0 ORGANIZATION OF THE MATERIAL

In any cataloguing of the hypersonic turbulent wake research project at DREV, the place of honour must be reserved for those reports dealing with the presentation of results from the final measurement programs. Section 4 lists the most important of these reports under such subheadings as "Velocity", "Mass Density and Temperature", "Charge Density" and "Turbulence". An attempt is also made to indicate the type of information or data which is provided in each report but no attempt is made to state any of the principal conclusions. Such information, at least in part, may be obtained by referring to the "Abstracts" of the various reports. These are available in Appendix A.

While the final results of the wake program are undoubtedly of most interest, in fact they represent only a minor portion of the total activity. The general objectives of the research were to make spatially resolved measurements in turbulent wakes but in order to achieve these, it was necessary to develop new types of instrumentation. At the beginning of the program, the only equipment available in ballistic ranges which had produced reliable data on wakes employed schlieren or microwave interferometric and cavity techniques. These had produced estimates of the integrated behavior of some variable across the wake and, to carry out the DREV program, it was necessary to develop instrumentation capable of making point measurements.

The turbulent wake program thus has two identifiable phases. In the first, special instrumentation was developed or adapted to make point measurements under the transient conditions in free wakes in ballistic ranges. This included developing the cooled-film anemometer equipment to beyond the state-of-the-art, adapting the recent electron beam fluorescence probe technology to ballistic ranges, adapting electrostatic and Langmuir probe techniques to the uncooperative transient hypersonic wake plasma and, finally, developing the sequential spark technique to the level of a laboratory instrument. Typically, the development of the special instrumentation look up to five years and was still continuing as late as 1969. In that year, the project was halted for a 'crash program' effort to find a solution for the problem of reflected shock waves in the ranges. The special instrumentation had been well developed by 1968 and it then became evident that shock waves were perturbing the measurements. After a satisfactory solution was found the green light was given for data collection with all the operational experiments.

The second phase included the final data-gathering firing program from January to December 1970 and the analysis and reporting effort which extended from January 1971 to about December 1972.

A great many documents rightfully belong to the instrumentation phase. For a "final report", these documents have considerably less importance than do those which deal with the results of the final measurements. Therefore, with some regret, lists of these early documents have been relegated to the Appendices of this report.

Appendix B, titled "Instrumentation Phase Reporting" is divided into several subdivisions: "General", "Special Instrumentation" (including subsections on the anemometer, electron beam, electrostatic probe and sequential spark experiments), "Supporting Instrumentation" and, finally, "Reflected Shock Problem". In each case, internal (or DREV) publications are distinguished from external (or open literature) publications.

Appendix C is titled "Data Collection and Analysis Phase Reporting" and includes the titles of all the reports which can be attributed to the second or final measurements phase of the program, including those of the major reports discussed in Section 4. This appendix is again divided into subdivisions: "Analytical Support", "Charge Density", "Mass Density and Temperature", "Turbulence", and "Velocity". Again internal publications are distinguished from external publications.

Appendix D contains a list of progress reports issued during the program. This list includes DREV memoranda containing the minutes of several technical review and direction meetings. Appendix E lists reports issued as a result of contracts to industry and universities for studies related to the turbulent wake research program at DREV. Finally, Appendix F lists presentations made by members of the DREV staff to various unclassified technical meetings during the years 1966 - 1971.

Throughout the appendices an effort has been made to cite each document only once, except where the same material has been published both as a DREV document and in the open literature.

4.0 PRINCIPAL FINAL RESEARCH REPORTS

This section provides a list of the most important final reports of the hypersonic turbulent wake project. These have been distributed under such subheadings as "Charge Density", Mass Density and Temperature", "Turbulence" and "Velocity". For each report, a very brief indication is given of the ambient conditions under which the data was obtained. More information on the principal conclusions of the various reports may be obtained by consulting the report abstracts, which are listed in Appendix A, or (preferably) the reports themselves.

4.1 Charge Density

Two reports, DREV R-670 and R-690, dealing with the results of the application of ion probe and electron probe techniques have been published. In DREV R-670, the ion density distributions in the wakes of 2.7 inch diameter spheres flown at 14,500 feet/second in nitrogen atmospheres at 7.6 and 20 torr were estimated by applying various available probe theories to the current measurements effected across wakes with survey arrays of ion probes. The ion distributions were assumed to have a gaussian form and the amplitude and width parameters of the distributions were determined over a range of axial distance extending from about 60 diameters to many hundreds of diameters behind the projectiles. The results were compared with electron density levels in the wake deduced from microwave interferometer measurements.

Report DREV R-690 describes the absolute measurement with Langmuir probes of the mean density level in the wakes of 2.7 inch diameter spheres flown at 14,500 feet/second in 10 torr air. The data apply mainly to the normalized radial distance (R/D) band defined by $0.8 \leq R/D \leq 1.1$, and cover the axial distance range from about 100 to 2000 diameters. The Langmuir probe estimates of electron density are supported by measurements made with an X_s-band microwave interferometer.

4.2 Mass Density and Temperature

Two reports, DREV R-683 and R-693 have been published giving the results of the measurements made with an electron beam fluorescence probe on the behavior of mass density and temperature in the wakes of 15,000 feet/second spheres and cones. DREV R-683 presents results obtained from the laminar wakes of one inch and 2.7 inch diameter spheres flown in 3.0 torr and 1.1 torr air atmospheres respectively, as well as results from the turbulent wakes of the same projectiles flown at 10 torr and 7.6 torr air respectively. Assuming an isobaric wake, temperatures were inferred from the density measurements by invoking the perfect gas laws. A gaussian profile was fitted to the radial distributions of the temperature data and a related profile to the mass density results. The amplitudes and widths of these distributions were used to construct graphs showing the behavior of mass density and temperature in laminar and turbulent hypersonic sphere wakes over axial distances ranging from 50 to 2000 diameters.

The results of electron beam probe measurements of the radial and axial dependence of mass density in the wakes of sharp cones are reported in DREV R-693. Two types of cones were employed: a 44° vertex angle, 1.0 inch base diameter model and a 20° vertex angle, 0.7 inch base diameter slender model. Both were flown at 15,500 feet/second in nitrogen atmospheres at 10 torr. The data extend over a 2000 drag diameter range of axial distance.

4.3 Turbulence

Two reports, DREV R-669 and DREV R-696, have been written to describe the results of investigations into the structure of hypersonic sphere wakes using ion and electron probes. Report R-669 contains information about the intermittency structure in the wakes of spheres. This was derived from a study of the intermittency observed in the signals from a transverse-survey array of ion probes immersed in the wakes of 2.7 inch diameter spheres flown at 14,500 feet/second in nitrogen at 7.6 and 20 torr. The results apply to the range of axial distance extending from just behind the projectile out to several hundreds of diameters in the wake.

Report R-696 describes the behavior of integral scales, for charge density fluctuations in turbulent wakes, obtained from an analysis of the fluctuating currents collected by free-molecular electron probes and continuum ion probes. All of the observations were made in the wakes of 2.7 inch diameter spheres flown at 14,500 feet/second. The scales obtained with Langmuir probes in sphere wakes in 10 torr air were comparable to scales deduced with ion probes in similar wakes in 7.6 and 20 torr nitrogen. The behavior of the mean space scale has been determined for the axial distance range extending from 60 to 1000 diameters.

A third report, DREV R-687, compiles schlieren data on the growth of turbulent cores of the wakes of various conical and spherical models fired in the DREV ranges during the research program. These results may be useful for relating measurements made at DREV with previous results obtained at other laboratories under different ambient conditions.

4.4 Velocity

Three DREV Reports, R-663, R-681 and R-682, and Technical Note 2029 summarize the data obtained at DREV on the properties of velocity distributions in the wakes of spheres and cones. Report R-682 describes the major contribution made by the sequential spark technique to knowledge of the behavior of the mean velocity in hypersonic sphere wakes. The radial distributions of velocity have been fitted with gaussian profiles and the amplitude and width parameters have been determined over a large range of axial distance, up to a few thousand diameters behind the projectiles. The effect of pressure has been examined, and measurements have been made at sphere velocities of 4,000, 9,200 and 14,500 feet/second. Report R-663 contains the results of observations made by survey arrays of double probes on the velocity distributions in the wakes of 14,500 feet/second spheres flown in nitrogen atmospheres. These results are in excellent agreement with those obtained with the sequential spark technique.

The results of the experimental study of velocity in the wakes of hypersonic cones are given in DREV R-681. Three basic cone shapes were flown: 0.7 inch base diameter, 20° included angle sharp and blunted cones and 1.0 inch base diameter, 44° included angle sharp cones. All the measurements were made on cones flown at 15,000 feet/second in 100 torr air atmospheres. Because of the variations in the velocity in the wakes of cones induced by different angles of attack, a great deal of supporting investigation was necessary to locate the measurements with respect to the position of the wakes, and it was found impossible to define radial distributions as in the case of sphere wakes. For this reason, DREV TN-2029 has been written to document all the velocity profile data obtained on cone wakes during the program.

5.0 CONCLUDING REMARKS

An important ARPA-sponsored review (1) of the status of hypersonic wake studies published in 1965 ended with recommendations for more work in specific areas. Prominent among them was a call for "extensive experimental investigation of the near wake flow in the laminar, transitional, and turbulent regimes of the wake, with attention focussed on obtaining average local properties, such as pressure, mass and electron density, temperature, velocity, and the like, along with fluctuations and the most important correlations for the above quantities". Not all of these subjects were investigated at the Defence Research Establishment, Valcartier, nevertheless it would be fair to claim that the recently concluded DREV turbulent hypersonic wake program has made a significant contribution to a greater understanding of many areas cited.

ACKNOWLEDGMENTS

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REFERENCE

1. Lykoudis, P.S., "A Review of Hypersonic Wake Studies". RAND/RM-4493 ARPA, also AIAA J., Vol. 4, No. 4, pp. 577-590, April 1966.

APPENDIX A

ABSTRACTS OF FINAL REPORTS

DREV R-646/71: The Sequential Spark Technique: A Tool for Wake Velocity Studies in Ballistic Ranges (Unclassified)

For more than six years, the Defence Research Establishment Valcartier (DREV) has been carrying out a program of investigation of turbulent wakes in its ballistic range facilities. One of the experimental techniques used in this program has been the sequential spark technique which makes use of electrical discharges (sparks) in sequence to measure velocity profiles in the wake of projectiles in free flight. This experimental technique is based on the formation of an ionized luminous path in the wake by a first spark and on the periodic re-illumination of the displaced ionized path by successive sparks. Open-shutter photography yields a profile of the displacement of the path which can be used to calculate the velocity. This unique technique has produced, since 1966, a wealth of velocity data on the wakes of hypersonic spherical and conical models in free flight. This report presents a comprehensive review of the sequential spark technique. A description is given of the equipment which has been designed to produce the sparks. A new technique developed to select and switch the position of the spark in an array of electrodes is also explained. This technique as applied to sphere wake measurements has permitted the production of multiple velocity profiles in the wake of the same projectile. Applied to cone wake measurements, the technique has been used to switch the spark to a position predetermined by a series of detectors used to locate the flight line of the projectile in the range. The recording and data reduction method is described. Accuracy and resolution of the technique are discussed. Finally typical results are given and environmental conditions under which the sequential spark technique is applicable are outlined.

DREV R-647/71: An Application of the Electron Beam Fluorescence Probe in Hyperballistic Range Wake Studies (Unclassified)

The electron beam fluorescence technique, used exclusively up to now in low density wind tunnels and shock tubes to measure gas density and temperature, has been applied to local mass density measurements in the wake of hypersonic models launched in free-flight hyperballistic ranges. The advantages and limitations of the technique in this application are discussed. The experimental apparatus is described and the signal analysis scheme is presented. Typical measurements of the mass density obtained in laminar as well as in turbulent wakes show the capabilities of the technique.

DREV R-648/72: Hypersonic Wake Studies Using Cooled-Film Anemometer Techniques (Unclassified)

The techniques of cooled-film anemometry have been applied to the determination of temperature and velocity distributions in the wakes of projectiles travelling at hypersonic speeds in a free flight range. The anemometer sensing element comprises a thin platinum film which is deposited on a section of a fine vycor loop through which a refrigerant can be circulated. A gold coating on the remainder of the loop provides an electric connection to a bridge circuit incorporating a feedback system which maintains the sensor at constant resistance and hence constant temperature for frequencies up to 50 kHz. Studies conducted in the wakes of projectiles travelling at 15,000 ft/sec in ambient pressures ranging from 1/10th to 1/1000th of an atmosphere have shown that the compressible hypersonic wake is essentially different from the low-speed incompressible wake. The latter degenerates rapidly into a fully developed turbulent flow, whereas the former exhibits at least a double structure comprising large-scale quasi-periodicity which persists due to the stabilizing influence of the stratification of vortical layers.

DREV R-654/72: Fluid Dynamic Properties of Turbulent Wakes of Hypersonic Spheres (Unclassified)

Of particular importance to the understanding and modeling of turbulent hypersonic wakes is the availability of reliable spatially resolved measurements of the behavior of such wake variables as velocity, mass density, temperature and charge density. An experimental program to obtain such measurements has recently been completed at the Defence Research Establishment Valcartier. The present paper reports on the mean values of velocity, density, and temperature in Mach 13 sphere wakes ($P_\infty D$ = 20 torr-inches), and also on such turbulent characteristics as the fluctuation levels, the scale lengths, and the intermittency found in the wake. As a test of the mean data, an attempt is made to use the measured velocity and density distributions to compute the momentum defect in the wake.

DREV R660/72: X_S-Band Microwave Interferometer for Study of Hypersonic Turbulent Wake on Range 5 (Unclassified)

As part of a research program aimed at determining the behavior of the mean and fluctuating charge density levels in an ionized turbulent wake, a dual channel microwave interferometric equipment operating at X_S-Band has been installed on the hypersonic Range 5 facility at Defence Research Establishment Valcartier (DREV) to provide an independent estimate of the mean electron density. Resolution of the order of 2 inches is provided by a double-lens focussing system, installed about the projectile line-of-flight. The present report describes in detail the horn-lens system, the transmission and receiving systems, and the calibration and analysis procedures. The analysis employed here goes somewhat beyond the conventional ballistic range practice of quoting a result indicative of the integration of a somewhat arbitrary electron density over an equally indefinite path length. Instead, on the basis of an assumed gaussian electron density distribution in the wake, the two measurements made with the dual channel equipment are used to infer both the amplitude and the width parameters of the assumed distribution function as a function of time or axial distance behind the projectile. Typical results are presented for the case of 2.7 inch diameter spheres flown at 14,500 feet/second in air.

DREV R-663/72: Velocity Mapping of Turbulent Wakes of Hypersonic Spheres with Arrays of Ion Probe Pairs (Unclassified)

The technique of measuring convection velocity in the hypersonic wake with a pair of in-line probes has been applied on a large scale to the mapping of the velocity field in the hypersonic wake through the use of a transverse survey array containing up to 8 ion-probe pairs. Measurements are reported of the velocity field in the wakes of 2.7 inch diameter spheres flown at 14,500 feet/second in ballistic range atmospheres at 7.6 torr and at 20 torr of nitrogen. The array technique leads to convection velocity results which are in excellent agreement with the mean wake velocity data obtained by the sequential spark technique in an air atmosphere. In addition, the technique has permitted an extension of the mapping of the velocity field of 15,000 feet/second spheres to considerably smaller axial distances than was possible with the spark method because of the difficulty of forming distinct sparks at the higher levels of ambient ionization encountered in the near wake.

A comparison of the data obtained at 7.6 torr and at 20 torr shows that the amplitude of the velocity distribution in the wake, as defined by the velocity on the wake axis, is higher at higher pressure. Considering the wake width however, it is found that the width of the velocity distribution is larger at the lower pressure of 7.6 torr than is the case at 20 torr, at least in the near wake. However, at axial distances greater than 300 or 400 diameters, the data for the two pressures

tend to overlap. These observations appear to be related to other information indicating that for 2.7 inch diameter spheres launched at 7.6 torr, the wake is not fully turbulent until about 300 or 400 diameters.

DREV R-664/73: The Application of Ion Probes to Wake Diagnostics (Unclassified)

The range of ambient conditions influencing current collection by an ion probe immersed in the wake of a 2.7 inch diameter sphere flown at 15,000 feet/second in atmospheres at various pressures has been examined; it is clear that the probe is immersed in a weakly ionized plasma and that current collection is collision-dominated.

The set of general equations required to derive the current collected by a biased probe in a weakly ionized, collision-dominated plasma flowing over the probe is given. The static theory of Zakharova and her coworkers and that of Schulz and Brown, which do not take account of plasma motion, are described. The theory of Kulgein, which allows for plasma motion, is also described. All three theories have been expressed in power law form, which permits an explicit representation of the dependence of the probe current on a product of factors for charge density, temperature, pressure velocity, and potential, each variable being raised to a certain exponent or power.

The power law forms for expressing the functional dependence of the probe current on the independent variables have been exploited to derive the effect on the mean current of variance and covariance coefficients of various variables when the probe is immersed in a turbulent wake. It is concluded that the mean current can be calculated from the power law forms using the mean values of the variables to an accuracy of 10 or 20% depending on which theory is applied.

The interpretation of the probe current fluctuations in terms of charge density fluctuations is considerably less certain and demands that $\overline{(\Delta Ne)^2}/\overline{Ne}^2$ be of the order of unity while other variances and covariances be small. Since the examples discussed in the text indicate that $(\overline{(\Delta Ne)^2})^{\frac{1}{2}}/(\overline{Ne})$ was only of order of 0.6, it is probable that the current fluctuations are dominated by charge density fluctuations but are not independent of fluctuations of the other variables in the wake.

The various probe theories have been applied to some preliminary probe current data obtained at Defence Research Establishment Valcartier (DREV). (This data has been obtained in the presence of reflected shock effects without supporting microwave interferometer mean charge density measurements). It is concluded, that the charge densities inferred from the kinematic theory of Kulgein are in better agreement with the theoretical predictions obtained from flow field calculations at AVCO Everett Research Laboratory, than are the densities inferred from the static theories of Zakharova or Schulz and Brown. These latter theories both predict considerably higher charge densities.

DREV R-669/72: Structure of Turbulent Wakes of Hypersonic Spheres as Inferred with Ion Probes (Unclassified)

Survey arrays of ion probes have been used to study the structure of the ionized turbulent wakes of 2.7 inch diameter spheres flown at 14,500 feet/second in atmospheres of nitrogen at pressures of 7.6 and 20 torr. For various radial distances measured from the wake axis, matrices of data points have been obtained giving random values of the axial distance behind the projectile at which ionization begins, the first ionized eddy occurs, and continuous turbulence begins. A wake radius separating the significantly ionized wake from the unionized wake has been obtained, and found to lie intermediate between the inviscid wake radius defined by Wilson from schlieren measurements and an electron density radius corresponding to the 1/e points of the electron density distribution defined by microwave interferometric measurements. A radius defining the extent of the ionized portion of the turbulent core has been determined; this radius is of the order of 80% of the schlieren radius of the turbulent core.

The continuous turbulence data can also be used to define a wake radius; this radius has been identified as the mean position of the turbulent interface for ionized eddies, because it is in agreement with estimates of the turbulent interface obtained by fitting the radial distributions of intermittency estimates prepared from independent 0.5 millisecond long segments of the ion probe signals. The radius corresponding to the mean position of the turbulent interface is within the schlieren radius of the wake core. In addition to determining the mean position of the turbulent front, the standard deviation of the interface has been established. These last data have been found to be in broad agreement with data derived from measurements of the wake edge using schlieren techniques.

The differences in the results obtained at 7.6 torr and 20 torr have been considered and found consistent with other experimentally measured data obtained at Defence Research Establishment Valcartier (DREV); the occurrence of a transitionary type behavior in the frequency content of the probe signals from the 7.6 torr results has been noted but not explained.

DREV R-670/72: Ion Density Measurements in the Wake of a Hypersonic Sphere (Unclassified)

A report is presented of the results of a major research effort undertaken to determine experimentally, through the use of cylindrical electrostatic probes and existing probe theory, the levels of ion density in the turbulent wakes behind 2.7 inch diameter spheres flown at 14,500 feet/second in a ballistic range filled with nitrogen at 7.6 torr and at

20 torr. The major problem encountered in this work is the one concerned with the theoretical interpretation of the ion current seen by an electrostatic probe in terms of ion density. The many theories which have been proposed can be divided into two main categories: the 'static' theories which do not consider the flow velocity of the plasma in which a probe is immersed and the 'kinetic' theories which attempt to take flow velocity into account. Generally speaking, the theories indicate that the current collected by an ion probe of convenient dimensions is not uniquely determined by the ion density, but also depends on such physical variables as the temperature, pressure, probe potential, and additionally, in the case of the 'kinetic' theories, on the bulk velocity of the medium. Where the 'problem' arises is in the fact that the probe theories differ in their predictions of the details of the dependence of the probe current on the various physical variables listed above.

Measurements of the ion current distribution across hypersonic sphere wakes have been made by means of a transverse survey array of cylindrical electrostatic ion probes. Three static theories and three kinetic theories have been applied to the mean current data of the probes, and with the aid of experimentally measured temperature and velocity distribution data for sphere wakes, used to construct radial distributions of ion density estimates for each theory. These radial distributions have been fitted with gaussian curves by the method of least mean squares. Two parameters of the ion density distributions are determined: the ion density on the axis of the wake and the ion density radius of the wake. These results have been compared with electron density levels in the wake deduced from microwave interferometer measurements and Langmuir probe instrumentation.

Concerning the ion density level on the wake axis, it is found that the static theories predict ionization levels which are an order of magnitude larger than those given by the kinetic theories at both 7.6 and 20 torr. In turn, the kinetic theories predict ion density levels which are higher than the electron density levels obtained with the interferometer. At 7.6 torr, the kinetic theories seem to be about a factor of five too high at 100 diameters behind the sphere, but at larger axial distances, (240 - 400 diameters) the ion density results of the ion probes, and the electron density results of the interferometer as well as the results of the Langmuir probe, are all within a factor of 2. However, at higher pressures (20 torr) the difference in the results increases and the kinetic theory ionization levels are about an order of magnitude higher than the microwave interferometer results. One of the conclusions from these results is that 'The Theory' of cylindrical electrostatic probes has yet to see the light of day. The predictions of all the diverse theories agree on one point: between the axial distances of 100 and 400 diameters, the ion density on the wake axis decays according to an $n_o \propto (X/D)^{-2}$ law. In addition to the results concerning ion density levels, interesting information has also been generated concerning the widths of the ion density profiles in the wake.

The report includes considerable information on the treatment of the probe current signals and on electrostatic probe theories, while Appendices include tables of data pertaining to the fitting of the ion density radial distributions derived from each of the theories, and graphs showing the evolution of the ion density radial distributions with axial distance behind the projectile.

DREV R-675/73: Summary Report on the Attenuation of Reflected Shocks in DREV Ballistic Range Facilities (Unclassified)

The objective of this report is to present a balanced account of the discovery, engineering and evaluation of the treatment used in the hypersonic ranges at the Defence Research Establishment Valcartier (DREV) for shock attenuation which could be consulted by any interested user of DREV turbulent wake data. This report also contains a description of how the reflected shock waves appear to affect the measurements, a résumé of the experimental research program as a result of which the smoothly-profiled fiberglas wedge treatment came to be selected over other candidates, and a description of the engineering and installation of the full scale treatments on Range 5 and Range 3. Finally there is included data obtained with pressure transducers and with electrostatic ion probes in the full scale shock attenuation treatment which is applicable to an assessment of its efficiency.

DREV R-680/72: Electron Density Behavior in the Wake of Spheres Flown at 14,500 feet/second (Unclassified)

The amplitudes and widths of the assumed gaussian distributions of electron density in the wakes of hypersonic spheres flown at 14,500 feet/second in atmospheres of air and nitrogen at various pressures have been derived from phase shift measurements with a dual channel interferometer operating at X_s-band. The data apply to the near wake extending from just behind the spherical projectile out to several hundreds of body diameters, and cover a band of electron number densities from 10^{11}/centimeter^3 to less than 10^9/centimeter^3. A conclusion of major importance is that it is possible to obtain reproducible electron density measurements under the normal operating conditions in the Defence Research Establishment Valcartier (DREV) Range 5. No data from other laboratories were found at sufficiently similar conditions to permit an exact comparison with the present results. However, the general trend of the data seems to follow that observed elsewhere.

DREV R-681/72: Experimental Study of Wakes Produced by Hypersonic Cones in Free Flight (Unclassified)

This paper describes an experimental study of the wakes produced by hypersonic cones flying at a velocity of 15,000 feet/second in Range 3 at the Defence Research Establishment Valcartier (DREV). Three basic cone shapes have been flown: 0.7 inch base diameter, 20° included angle cones with sharp and blunted noses and a 1.0 inch base diameter, 44° included angle sharp nose cone. Because of the complexity of the flow field generated by these cones usually flying at some angle of attack, the experimental study was limited to one set of ambient conditions, namely, a cone velocity of 15,000 feet/second and an ambient pressure of 100 torr of air.

The measurement of the wake velocity distribution by means of the sequential spark technique constituted the backbone of the experimental program on cone wakes. The technique is based on the formation of an ionized luminous path in the wake by a first spark and on the periodic re-illumination of the displaced ionized path by successive sparks. Over one hundred profiles of velocity were measured behind the cone shapes. Additional diagnostic tools for this study included the photoattitude and velocity measurement system of the range which was used to determine the flight history and to measure the drag coefficient of the models and deflection. A wealth of original data has been obtained on the behavior of the wake generated by the three different conical models. The measurements have revealed the presence of an asymmetry in the transverse profile of axial velocity and the presence of a lateral velocity component in the wake of high lift to drag ratio cones flying at angle of attack. The variation of the wake axis and wake front velocity with axial distance has been derived and shows good agreement with other theoretical and experimental results. Due to the presence of angles of attack of different amplitude and orientation, it was not possible to determine the transverse distribution of the mean axial velocity. Nevertheless, these results should contribute to a better understanding and also to an accurate modeling of the wake of cones.

DREV R-682/72: Velocity Distributions of Sphere Wakes (Unclassified)

The present report is concerned with the wake velocity results measured in sphere wakes with the sequential spark technique. This technique has been employed to measure the radial distribution of velocity in the turbulent wakes of spheres flown at Mach numbers from 3.5 to 13 and at Reynolds' numbers from 0.2×10^6 to 10^6 over a range of axial distance extending up to 3500 diameters. For each selected combination of velocity, pressure, sphere diameter and axial distance, a sufficient number of firings have been observed so as to permit the statistically meaningful

determination of the mean profile of velocity. On 14,500 feet/second spheres, wake velocity mean characteristics were determined for ambient $P_\infty D$ (pressure times sphere diameter) values of 20, 40 and 100 torr-inches. The results showed only a weak dependence of the wake velocity on $P_\infty D$. Measurements were also made at sphere velocities of 9,000 and 4,000 feet/second at a $P_\infty D$ value of 100 torr-inches. The measurements revealed a strong influence of the Mach number on the wake velocity in the intermediate region of the wake. One of the important findings, observed under all the test conditions, is that the radial distribution of mean axial velocity in the turbulent wake is well approximated by a gaussian curve.

DREV R-683/72: Density and Temperature Distributions in Hypersonic Sphere Wakes (Unclassified)

The radial and axial dependence of the mass density distributions in both the laminar and the turbulent wakes of 1.0 and 2.7 inch diameter spheres flown at Mach 13.5 in nitrogen atmospheres have been determined using the electron beam fluorescence probe technique. The distribution of temperature in the wake has also been inferred by invoking the assumption that the wake is isobaric. Both the mass and the temperature distributions in the wake may be characterized by the behavior of two parameters: the amplitude of the mass density or temperature on the centreline of the wake, and the corresponding profile width. Experimental data are presented for these parameters.

DREV R-687/73: Growth Characteristics of Turbulent Wakes (Unclassified)

Recent advances in the experimental study of hypersonic wakes at the Defence Research Establishment Valcartier have led to spatially resolved measurements of the behavior of the important physical variables which characterize the wake. Previous measurements pertained mainly to the wake growth and they were achieved by an integrated-type technique using a schlieren system under test conditions different from those utilized at this Establishment. To assist in relating the new measurements with the earlier ones, and to provide a basis for comparing growth results obtained from the spatially resolved measurements, schlieren films of model wakes taken during the DREV program have been utilized to obtain wake growth data at the same velocities and pressures as those of the spatially resolved measurements. Both cone and sphere wakes have been investigated. Results show that the effect of $P_\infty D$ (pressure times body diameter) on wake growth is negligible, while Mach number has a strong effect. Turbulent wake growth can be described by the following expression:

$$D_W/\sqrt{C_D A} = C(X/\sqrt{C_D A})^{1/3},$$

Where both the wake width D_w and the axial distance X have been normalized by the drag diameter $\sqrt{C_D A}$. The factor C is a function of the Mach number M_∞,

$$C = 0.56 + 0.032 M_\infty.$$

DREV R-690/73: Absolute Electron Density Measurements in Turbulent Sphere Wakes with Langmuir Probes (Unclassified)

Measurements were carried out in the ballistic range facilities at DREV of the absolute electron density levels in the wakes of 2.7 inch diameter spheres flown at 14,500 feet/second in air atmospheres at 10 torr. The experimental technique involved the use of Langmuir probes, following the theoretical demonstration of feasibility of such an experiment by G.W. Sutton. Considerable attention was paid to details of the experiment, such as probe cleanliness, minimum flow disturbance and the minimization of reflected shocks. Electron density level estimates obtained with the Langmuir probes were in good agreement with electron density estimates derived from simultaneous measurements with a microwave interferometer. The behavior of the plasma potential in the wake was also determined; the plasma potential apparently attempted to maintain itself close to the potential of the most highly biased probes, but the reason for this behavior has not been established. This Report concludes with suggestions for further utilization of the equipment.

DREV R-695/73: Density and Temperature Distributions in Hypersonic Cone Wakes (Unclassified)

This report presents mass density measurements performed in the wake of hypersonic cones in free flight using the electron beam fluorescence probe technique. The radial and axial mass density distributions have been obtained in the wake of sharp nose cones with vertex angles of 44° and 20° launched at 15,500 feet/second in a nitrogen atmosphere at 10 torr. The corresponding temperature distributions have been inferred from the density data by assuming that the wake is isobaric and that the perfect gas law is valid a short distance behind the model.

DREV R-696/73: Behavior of Turbulent Scales in Hypersonic Sphere Wakes (Unclassified)

The behavior of macroscales associated with the charge density fluctuations in the turbulent wakes of hypersonic spheres has been investigated using both Langmuir electron probes and continuum electrostatic ion probes. When cylindrical Langmuir probes are operated under favourable conditions, theoretical analysis indicates that the statistics of the probe current fluctuations are representative of the statistics of the electron density fluctuations. Similar analysis for continuum ion probes indicates however that the statistics of the current fluctuations depend not only on the ion density fluctuations but are possibly also strongly influenced by correlation functions involving temperature or velocity fluctuations.

Nevertheless, in the present experiments involving probe measurements in the wakes of 2.7 inch diameter spheres flown at 14,500 feet/second in 10 torr air and in 7.6 and 20 torr nitrogen atmospheres, macroscale measurements with ion probes appear to be equivalent to macroscale measurements from Langmuir probes. This result greatly increases the credence of the ion probe macroscale data which, in fact, are considerably more extensive than those obtained with Langmuir probes.

The mean macroscales obtained at DREV with ion probes decrease in magnitude as axial distance increases between 100 and 1000 diameters; the Langmuir probe results which extend to slightly larger axial distances indicate the mean scale begins to increase again between 1000 and 2000 diameters. For axial distances less than 400 diameters, the ion probe results also indicate a significant dependence of the mean macroscale on the paramter $P_{\infty}D$. When compared with previous macroscale results obtained in sphere wakes by a variety of techniques, the DREV measurements appear to fit into a general pattern in which the mean macroscale first decreases and then increases with increasing axial distance. This same comparison indicates that the mean macroscale behavior is dependent on sphere velocity.

DREV TN-1998/72: Resolution of the Microwave Lens System in an X_s-Band Interferometer (Unclassified)

A dual channel focused beam X_s-Band microwave interferometer has been installed on the DREV Hypersonic Range 5 facility to provide estimates of mean electron density levels simultaneously with electrostatic probe and microwave scattering measurements in the turbulent

wakes of hypersonic spheres. As part of the assessment of this equipment, a survey has been undertaken of the field intensity in the image space of the system. The field pattern measurements were made on a single double plano-convex lens, mounted in a standard optical bench which was fitted with a traversing bar mechanism carrying the field probe apparatus. Intensity field patterns, derived by transverse scans at various axial distances from the lens, were subsequently used to derive contour plots of field intensity in the plane containing the axis of the lens. In the focal plane of the lens, the beam spot size is W = 2.0 inches for the -3 dB 'isophote' and 3.2 inches for the -10 dB 'isophote'. In terms of the size of a 2.7 inch diameter sphere, a beam width of 2.0 inches = 0.74 diameters; this resolution is considered adequate for the study of the values of such spheres. Some differences in existing criteria for depth-of-field have been discussed; if one is prepared to allow up to 20% variation in beam width, the effective depth-of-field in the lens system is 12 inches, or 5 sphere diameters. This depth-of-field is adequate for study of the first 400 diameters of a sphere wake (based on the measured schlieren radius).

DREV TN-2028/72: Le problème du lissage (Non classifié)

This note describes various FORTRAN and/or APL computer programs intended to solve the problem of fitting all sorts of functions to a series of experimental points. The first part presents an APL program which may be used to solve linear regressions. This program possesses some useful characteristics. For example, besides giving an analysis of variance, it computes a confidence interval for the fitted values of the parameters as well as a confidence interval for the predicted values of the dependent variable. The second part deals with nonlinear regressions. Two versions, one in FORTRAN language and one in APL language, of a program for the solution of any kind of nonlinear regression are described. Another FORTRAN program which permits the determination of confidence contours for the parameters of the fitting function is also described. The appendices contain a listing of all these programs along with working examples.

DREV TN-2029/72: Cone Wake Velocity Profiles Measured by Means of the Sequential Spark Technique (Unclassified)

The purpose of this Note is to document the velocity profiles measured with the sequential spark technique during the program of study of cone wakes. Due to the presence of angles of attack of different amplitude and orientation with respect to the spark traces, it has not been possible to determine the transverse distribution of the mean axial velocity as was done in the case of spheres. The use of these profiles has been limited to the determination of characteristics of wake axis and

wake front velocities and to the visualization of the skewness of the transverse profile of axial velocity. The data however, contain additional information on the wake structure which cannot be extracted presently because of lack of statistical data but which could be of interest to specialists in the field.

DREV M-2205/72: Détermination de la Densité Ionique: Dépouillement et Traitement des Signaux de Sondes (Non classifié).

This memorandum reviews the various steps in the signal processing and data analysis of electrostatic probe signals leading to the determination of the ion density in the midst of the ionized wake produced by a hypersonic sphere. The experimental setup and the recording system are very briefly summarized. However, the processes of digitalization of the analog traces and the storing on magnetic tapes of the correlation functions of the resulting digital traces are fully described. A large section of the memorandum is devoted to the identification of the various errors that might affect the value of the mean current collected by a probe (and consequently the value of the ion density), and to the appropriate corrections. Finally the mathematical formulations of six different ion collection theories as well as mathematical expressions for the velocity field and the temperature field of a 2.7 inch sphere at 7.6 torr and 20 torr are given. The appendices contain several computer program listings used for the analysis.

DREV M-2225/72: Comparison of Sphere Wake Velocity and Temperature Data Obtained at DREV by Several Experimental Techniques (Unclassified)

The Defence Research Establishment Valcartier (DREV) has since 1965 carried out a program of activities aimed at the experimental determination of the behavior of mass density, temperature, velocity and charge density in hypersonic turbulent wakes. During the program it has been found possible to measure the same wake variable by more than one experimental technique. For example, velocity has been measured by the sequential spark technique, arrays of electrostatic probes and by the 2-temperature cooled-film anemometer technique. Temperature has been inferred from the electron beam fluorescence probe measurements of mass density and from the anemometer results. In this memorandum, velocity and temperature data obtained with the cooled-film anemometer in the wakes of 2.7 inch diameter spheres flown at 14,500 feet/second are compared with sequential spark velocity results and the electron beam temperature measurements. The comparison indicates discrepancies somewhat larger than had been anticipated.

APPENDIX B

INSTRUMENTATION PHASE REPORTING

B.1 General

Internal Publications

1. Heckman, D., "Re-entry physics research program on turbulent wakes", CARDE TN 1741/67, January 1967. (Unclassified).

2. Lemay, A., "The CARDE turbulent hypersonic point measurement program", CARDE TN 1772/67, October 1967. (Unclassified).

3. Heckman, D., Lahaye, C. and Tardif, L., "Experimental Study of turbulent wakes free-flight ranges", CARDE TR 595/68, September 1968. (Unclassified).

External Publications

1. Heckman, D., Tardif, L. and Lahaye, C., "Experimental study of turbulent wakes in the CARDE free-flight ranges", Proceedings of the Symposium on Turbulence of Fluids and Plasmas, April 16 - 18, 1968, Microwave Research Institute Symposia Series, Vol. XVIII, Polytechnic Press of the Polytechnic Institute of Brooklyn, N.Y., 1969.

2. Tardif, L., Lahaye, C., Heckman, D., Ellington, D. and Dionne, J.G.G., "Point Measurements in the Wake", Chapter XI of Ballistic Range Technology, AGARDograph 138-70, edited by A. Seiff, T.N. Canning, and C.S. James, 1970.

3. Lemay, A., "Research in Hypersonic Wakes", ICAS Paper No. 70-07, International Council of the Aeronautical Sciences, Rome, September 1970.

B.2 Special Instrumentation

B.2.1 Anemometer Experiment

Internal Publications

1. Trottier, G., Ahmed, A.M. and Ellington, D., "Cooled-film anemometer measurements in the hypersonic wake", CARDE TN 1720/66, May 1966. (Unclassified).

2. Ellington, D. and Trottier, G., "Some observations on the application of cooled-film anemometry to the study of the turbulent characteristics of hypersonic wakes", CARDE TN 1773/67, September 1967. (Unclassified).

3. Ahmed, A.M., "Forced convective heat transfer to cooled cylinders at low Reynolds numbers and with large temperature differences", CARDE TR 588/68, September 1968. (Unclassified).

4. Ellington, D., Picard, A.G. and Park, K.R., "Cooled-film anemometer - sensor open loop response", DREV TN 1901/70, October 1970. (Unclassified).

5. Ellington, D., Park, K.R. and Desjardins, P., "Hypersonic wake studies using the cooled-film anemometer technique", DREV R 648/71, September 1972. (Unclassified).

External Publications

1. Ellington, D. and Trottier, G., "Some observations on the application of cooled-film anemometry to the study of the turbulent characteristics of hypersonic wakes", "Advances in Hot-Wire Anemometry", W.L. Melnik and J.R. Weske, Editors, Proceedings of the International Symposium on Hot-Wire Anemometry, held at University of Maryland, March 20 - 21, 1967.

2. Ellington, D. and Trottier G., "Studies of the turbulence in the wakes of hypersonic spheres under simulated re-entry conditions, AGARD Conference Proceedings No. 19 on the Fluid Physics of Hypersonic Wakes, May 1967.

3. Ellington, D., Park, K.R. and Desjardins, P., "Hypersonic wake studies using cooled-film anemometer techniques, ICIASF'71 Record of the 4th International Congress on Instrumentation in Aerospace Simulation Facilities, 71-C-33 AES, 45 - 59, June 1971.

B.2.2 Electron Beam Experiment

Internal Publications

1. Tardif, L. and Dionne, J.G.G., "Space-resolved wake-density measurements", CARDE TN 1724/66, June 1966. (Unclassified).

2. Sadowski, C. and Vanoverschelde, J.E.H., "The measurement of mass density in a turbulent wake by means of Rayleigh scattering from a laser beam", CARDE TN 1764/67, December 1967. (Unclassified).

3. Dionne, J.G.G., Sadowski, C.M., Tardif, L. and Vanoverschelde, J.E.H., "Mass density measurements in hypersonic wakes", CARDE TN 1780/67, December 1967. (Unclassified).

4. Dionne, J.G.G. and Tardif, L., An application of the electron beam fluorescence probe in hyperballistic range wake studies", DREV R 647/71, September 1971. (Unclassified).

External Publications

1. Dionne, J.G.G., Sadowski, C.M., Tardif, L. and Vanoverschelde, J.E.H., Mass density measurements in hypersonic wakes", AGARD Conference Proceedings No. 19 on the Fluid Physics of Hypersonic Wakes, May 1967.

2. Tardif, L. and Dionne, J.G.G., "Density distribution in turbulent and laminar wakes", AIAA J. 6, 19, 2027-29, October 1968.

3. Dionne, J.G.G. and Tardif, L., "On the application of the electron beam fluorescence probe in hyperballistic range wake studies", ICIASF'71 Record of the 4th International Congress on Instrumentation in Aerospace Simulation Facilities, 71-C-33 AES, 80-86, June 1971.

B.2.3 Electrostatic Probe Experiment

Internal Publications

1. Kirkpatrick, A., Cantin, A., Heckman, D. and Gravel, M., "Preliminary electron conductivity probe results at CARDE, CARDE TN 1719/66, May 1966. (Unclassified).

2. Kirkpatrick, A., "Measurements of response times of CARDE conductivity probes at AVCO Research Laboratories", CARDE TN 1727/66, July 1966. (Unclassified).

3. Cantin, C. and Gagné, R.R.J., "Difficultés inhérentes à l'emploi de sondes électrostatiques dans un plasma h.f.", DREV TN 1861/70, juin 1970. (Unclassified).

4. Cantin, A., "The application of ion probes to wake diagnostics", DREV R 664/73, May 1973. (Unclassified).

External Publications

1. Heckman, D., Cantin, A. and Kirkpatrick, A., "Electrostatic probe measurements in the turbulent wake of hypersonic spheres fired in a ballistic range", AGARD Conference Proceedings No. 19 on the Fluid Physics of Hypersonic Wakes, May 1967.

2. Kirkpatrick, A., Heckman, D. and Cantin, A., "Wake plasma turbulence study using an electrostatic probe array", AIAA J. 5, 8, 494-495, August 1967.

3. Cantin, A. and Gagné, R.R.J., "The proper use of electrostatic probes in electrodeless RF plasmas", IEEE Trans. AP-16, 2, 279-282, March 1968.

4. Heckman, D., Emond, A. and Sévigny, L., "Some results of electrostatic probe studies of turbulent hypersonic wake plasmas", Preprint No. 68-689, AIAA Fluid and Plasma Dynamics Conference, June 1968.

5. Cantin, A., Emond, A. and Heckman, D., "Observations on electrostatic probe behavior in collision-dominated ionized turbulent gas flows in ballistic ranges", ICIASF'69 Record of the 3rd International Congress on Instrumentation in Aerospace Simulation Facilities, 69-C-19 AES, 20-23, May 1969.

6. Heckman, D., Emond, A., Fitchett, A. and Sévigny, L., "Mean and fluctuating charge density measurements in turbulent hypersonic sphere wakes", ICIASF'71 Record of the 4th International Congress Instrumentation in Aerospace Simulation Facilities, 71-C-33 AES, 45-59, June 1971.

B.2.4 Sequential Spark Experiment

Internal Publications

1. Lahaye, C., Léger, E.G., Hubbard, F. and Lemay, A., "The sequential spark measurement of the radial velocity profiles of wakes produced by hypersonic projectiles", CARDE TN 1771/67, October 1967. (Unclassified).

2. Lahaye, C., Léger, E.G., Dufresne, M., Doyle, H. and Boucher, P., "The sequential spark technique: a tool for wake velocity studies on ballistic ranges", DREV R 646/71, November 1971. (Unclassified).

External Publications

1. Lahaye, C., Léger, E.G. and Lemay, A., "Radial and axial velocity profiles of hypersonic and supersonic wakes measured by the sequential spark method", AGARD Conference Proceedings No. 19 on the Fluid Physics of Hypersonic Wakes.

2. Lahaye, C., Léger, E.G. and Lemay, A., "Wake velocity measurements using a sequence of sparks", AIAA J. 5, 12, 2274-76, December 1967.

3. Lahaye, C., Léger, E.G., Dufresne, M., Doyle, H. and Boucher, P., "The sequential spark technique: a tool for wake velocity studies in ballistic ranges", ICIASF'71 Record of the 4th International Congress on Instrumentation in Aerospace Simulation Facilities, 71-C-33 AES, 33-44, June 1971.

B.3 Supporting Instrumentation

Internal Publications

1. Tardif, L., "An oscilloscope photograph scanner", CARDE TR 510/64, July 1964. (Unclassified).

2. Léger, E.G. and Beaulieu, R., "Stereo flash X-ray photoattitude station for use on ballistic ranges", CARDE TR 563/67, April 1967. (Unclassified).

3. Doyle, H., "Repetitive point source spark gap having a 20 microsecond or longer repetition time", CARDE TN 1774/67, October 1967. (Unclassified).

4. Gravel, M., Heckman, D. and Tremblay, R., "Microwave studies in ballistic ranges", CARDE TN 1775/67, December 1967. (Unclassified).

5. Tardif, L., "Transitorized pulser for neon lamp time marker", CARDE TN 1786/68, February 1968. (Unclassified).

6. Tardif, L., "Analog recording system of microsecond resolution over a 0.2 second recording period", CARDE TN 1808/68, September 1968. (Unclassified).

7. Fitchett, A., "Microwave scattering experiment on hypersonic turbulent wakes", CARDE TN 1789/68, May 1968. (Unclassified).

8. Boucher, P., "A projectile detection system for dump tank of hypersonic ranges", DREV TN 1832/69, June 1969. (Unclassified).

9. Fitchett, A., "Microwave scattering experiment in hypersonic turbulent wakes. II. Further development of the equipment", DREV TN 1875/70, May 1970. (Unclassified).

10. Hubbard, F., "A study of possible causes of wake contamination of Range 5 rounds", DREV TN 1845/70, November 1970. (Unclassified).

11. Doyon, P. "The DREV hypersonic range No. 5 black and white schlieren", DREV TN 1920/71, April 1971. (Unclassified).

12. Doyon, P., "High sensitivity color schlieren photography of hypervelocity models at DREV hypersonic Range No. 5, DREV TN 1948/71, May 1971. (Unclassified).

13. Doyle, H., "Simultaneous double point source light generator", DREV M-2105/71, May 1971. (Unclassified).

14. Moir, L. and Dufresne, M., "Strip film recording of extremely fast digital data", DREV TN 1863/71, May 1971. (Unclassified).

15. Morency, J.P., "Experimental studies of a confined supersonic jet", DREV TN 1911/71, May 1971. (Unclassified).

16. Boucher, P., "Projectile detectors for hypersonic ranges", DREV TN 1915/71, May 1971. (Unclassified).

17. Fitchett, A., "Resolution of the microwave lens systems used in an X_s-band interferometer, DREV TN 1998/ 72, May 1972. (Unclassified).

18. Gagné, N., Fitchett, A. and Heckman, D., "X_s-band microwave interferometer for study of hypersonic turbulent wake on Range 5", DREV R 660/72, November 1972. (Unclassified).

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1. Moir, L.E., "Measurement of stagnation point temperature with high-g telemetry", published in the Proceedings of the 2nd International Congress on Instrumentation in Aerospace Simulation Facilities, (ICIASF), Stanford University, August 1966.

2. Gravel, M., Heckman, D. and Tremblay, R., "Microwave studies in ballistic ranges", Chapter X of Ballistic Range Technology, AGARDograph 138-70, edited by A. Seiff, T.N. Canning, and C.S. James, 1970.

B.4 Reflected Shock Problem

Internal Publications

1. Robertson, W.J., "The effect of reflected shock systems on hypersonic wakes", DREV TN 1846/69, October 1969. (Unclassified).

2. Moir, L. and Podesto, B., "Study of anechoic fiberglas wedge shock attenuation treatment using pressure gauges", DREV TN 1852/69, November 1969. (Unclassified).

3. Devereux, F., Doyon, P., Fitchett, A., Heckman, D., Moir, L. and Tardif, L., "Shadowgraph-schlieren and pressure gauge measurements on shock reflection and attenuation at atmospheric pressure", DREV TN 1871/70, March 1970 (Unclassified).

4. Heckman, D. and Emond, A., "Comparison of scaled shock attenuation treatments using electrostatic probes to detect residual wake deflection behind hypersonic spheres", DREV R 615/70, April 1970. (Unclassified).

5. Lahaye, C. and Doyon, P., "Universality of the reflected shock problem in cylindrical ballistic ranges", DREV TN 1862/70, April 1970. (Unclassified).

6. Devereux, F., Emond, A. and Heckman, D., "Scaled model evaluation of shock attenuation treatment for ballistic ranges", DREV TN 1895/70, July 1970. (Unclassified).

7. Lahaye, C. and Jean, L., "Tests on a full-scale conical deflector system for shock elimination", DREV TN 1894/70, September 1970. (Unclassified).

8. Podesto, B., "Pressure transducer measurements in full-scale models of proposed shock attenuation treatments for DREV ballistic ranges", DREV TN 2031/72, November 1972. (Unclassified).

9. Heckman, D., Williams, J., Robertson, W., Podesto, B. and Emond, A., "Summary report on the attenuation of reflected shocks in DREV ballistic ranges", DREV R 675/73, January 1973, (Unclassified).

External Publications

1. Heckman, D., Lahaye, C., Moir, L., Podesto, B. and Robertson, W., "A shock attenuation treatment for ballistic ranges", AIAA J. 9, 7, 1355-57, July 1970.

2. Cloutier, M., Devereux, F., Doyon, P., Fitchett, A., Heckman, D., Moir, L. and Tardif, L., "Reflections of weak shock waves from acoustic materials", Jour. Acous. Soc. Amer. 50, 5, 1393-96, November 1971.

3. Heckman, D., Williams, J., Robertson, W., Podesto, B. and Emond, A., "On minimizing the effects of reflected shocks in ballistic ranges", (submitted to IEEE Trans. AES).

APPENDIX C

DATA COLLECTION AND ANALYSIS PHASE REPORTING

C.1 Analytical Support

Internal Publications

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4. Gouge, R., Cantin, A. and Heckman, D., "A cross-correlation computer program for correlating pairs of random signals", CARDE TN 1788/68, June 1968. (Unclassified).

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8. De Carufel, J., Lahaye, C. and Sévigny, L., "Etude du coefficient de traînée en fonction de l'angle d'attaque pour des cônes", DREV TN 1936/70, October 1970. (Unclassified).

9. Sévigny, L., Caron, P. and Heckman, D., "Détermination de la densité ionique: dépouillement et traitement des signaux de sondes", DREV M-2205/72, May 1972. (Unclassified).

10. Sévigny, L., "Le problème du lissage", DREV TN 2028, December 1972. (Unclassified).

C.2 Charge Density

Internal Publications

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2. Heckman, D., Sévigny, L., Fitchett, A., Emond, A. and Doyon, P., "Electron density behavior in the wake of 14,500 feet/second spheres", DREV R 680/72, December 1970. (Unclassified).

3. Heckman, D., Sévigny, L. and Emond, A., "Absolute electron density measurements in turbulent hypersonic sphere wakes with Langmuir probes", DREV R 690/73, October 1973. (Unclassified).

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2. Dionne, J.G.G. and Tardif, L., "Density and temperature distributions in hypersonic sphere wakes", DREV R 683/72, December, 1972. (Unclassified).

3. Dionne, J.G.G. and Tardif, L., "Density and temperature distributions in hypersonic cone wakes", DREV R-695, August 1973. (Unclassified).

4. Heckman, D. (Editor), "Comparison of sphere wake velocity and temperature data obtained at DREV by several experimental techniques", DREV M-2275/72, September, 1972. (Unclassified).

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C.4 Turbulence

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2. Heckman, D. and Sévigny, L., "Structure of turbulent wakes of hypersonic spheres as inferred with ion probes", DREV R 669/72, August 1972. (Unclassified).

3. Lahaye, C. and Doyon, P., "Growth characteristics of turbulent wakes", DREV R-687, May 1973. (Unclassified).

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8. Ellington, D., "Cooled-film anemometer, data analysis of round 5078.70", DREV M-2144/71, December 1971. (Unclassified).

9. Ellington, D., "Cooled-film anemometer, data analysis of round 5079.70", DREV M-2145/71, December 1971. (Unclassified).

10. Ellington, D., "Cooled-film anemometer, data analysis of round 5080.70", DREV M-2146/71, December 1971. (Unclassified).

11. Ellington, D., "Cooled-film anemometer, data analysis of round 5081.70", DREV M-2147/71, December 1971. (Unclassified).

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13. Ellington, D., "Cooled-film anemometer, data analysis of round 5083.70", DREV M-2149/71, December 1971. (Unclassified).

14. Ellington, D., "Cooled-film anemometer, data analysis of round 5084.70", DREV M-2150/71, December 1971. (Unclassified).

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16. Ellington, D., "Cooled-film anemometer, data analysis of round 5086.70", DREV M-2152/71, December 1971. (Unclassified).

17. Ellington, D., "Cooled-film anemometer, data analysis of round 5087.70", DREV M-2153/71, December 1971. (Unclassified).

18. Ellington, D., "Cooled-film anemometer, data analysis of round 5088.70", DREV M-2154/71, December 1971. (Unclassified).

19. Ellington, D., "Cooled-film anemometer, data analysis of round 5089.70", DREV M-2155/71, December 1971. (Unclassified).

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3. Sévigny, L., Tardif, L., Dionne, J.G.G., Heckman, D. and Lahaye, C., "Hypersonic wake studies", CASI J. 19, 6, 279-88, July 1973.

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5. Lahaye, C., "Velocity distributions of sphere wakes", DREV R 682/72, December 1972. (Unclassified).

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APPENDIX D

PROGRESS REPORTING

D.1 Progress Reports

Internal Publications

1. The Staff of Aerophysics Wing. "Wake Turbulence Program". Progress Report May 1965. CARDE TN 1672/65. (Unclassified).

2. Aerophysics Wing Staff. "Re-Entry Physics Research Program on Turbulent Wakes". Semi-Annual Progress Report. Period 1 January - 30 June 1966. CARDE TN 1727/66. (Unclassified).

3. Aerophysics Wing Staff. "Re-Entry Physics Research Program on Turbulent Wakes". Semi-Annual Progress Report. Period 1 July - 31 December 1977. CARDE TN 1747/67. (Unclassified).

4. Aerophysics Division Staff. "Re-Entry Physics Research Program on Turbulent Wakes". Semi-Annual Progress Report. Period 1 July - 31 December 1967. CARDE TN 1787/68. (Unclassified).

5. Aerophysics Division Staff. "Re-Entry Physics Research Program on Turbulent Wakes". Semi-Annual Progress Report. Period 1 January - 30 June 1968. CARDE TB 1807/68. (Unclassified).

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9. Aerophysics Division Staff. "Re-Entry Physics Research Program on Turbulent Wakes". Semi-Annual Progress Report. Period 1 January - 31 July 1970. DREV TN 1932/71. (Unclassified).

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D.2 Minutes of Meetings

Internal Publications

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APPENDIX E

INDUSTRIAL AND UNIVERSITY CONTRACT REPORTING

Publications

1. Carswell, A.I. and Richard, C., "Focussed microwave systems for plasma diagnostics", RCA Victor Research Report No. 7-801-32, December 1964.

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3. Richard, L. and Rouillard, M., "Diffusion des micro-ondes par un sillage hypersonique turbulent, 2 - Spectromètre micro-onde pour l'étude de la diffusion par des structures diélectriques non uniformes", Université Laval, Départment de Physique, décembre 1966.

4. Gravel, M. and Tremblay, R., "Diffusion des micro-ondes par un sillage hypersonique turbulent, 1 - Méthodes de diversité", Université Laval, Département de Physique, mai 1967.

5. Fédotowsky, A. and Sen, A.K., "Scattering of an arbitrarily polarized plane wave from an inhomogeneous dielectric or under dense plasma using the Born approximation. Part I", Université Laval, Département de Physique, novembre 1967.

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8. Eichelbrenner, E.A., "Investigation of the development of laminar and turbulent boundary layers towards the rear of bodies in flight: the three-dimensional boundary layer on a circular cone place at small incidence in a supersonic flow with moderate Mach number,
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9. Baril, M. and Carette, J.D., "Rapport final concernant la modification de la source d'ion du spectromètre de masse à temps de vol (Bendix)", Université Laval, Départment de Physique, juin 1971.

APPENDIX F

PRESENTATIONS BY DREV STAFF

1. Dionne, J.G.G., "Instrumentation for hypersonic turbulent wake studies", paper presented to Aeroballistic Range Association, Institut Franco-Allemand de Recherches de Saint-Louis, (Haut Rhin), France, September 1966.

2. Ellington, D. and Trottier, G., "Some observations on the application of cooled-film anemometry to the study of the turbulent characteristics of hypersonic wakes", presented to the International Symposium on Hot-Wire Anemometry held at the University of Maryland, 21-22 March 1969.

3. Dionne, J.G.G., Sadowski, C.M., Tardif, L. and Vanoverschelde, J.E.H., "Mass density measurements in hypersonic wakes". presented to the AGARD Specialists Meeting on the Fluid Physics of Hypersonic Wakes, held at Colorado State University, Fort Collins, Colorado, 10-12 May 1967.

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5. Heckman, D., Cantin, A. and Kirkpatrick, A., "Electrostatic probe measurements in the turbulent wake of hypersonic spheres fired in a ballistic range", presented to the AGARD Specialists Meeting on the Fluid Physics of Hypersonic Wakes, held at Colorado State University, Fort Collins, Colorado, 10-12 May 1967.

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9. Tardif, L., "Laser beam adjustment system", presented to the 14th ARA Meeting, 12-14 June 1968.

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12. Cantin, A., Emond, A., Heckman. D., "Observations on electrostatic probe behavior in collision-dominated ionized turbulent gas flow in ballistic ranges", presented to the 3rd IEEE International Conference on Instrumentation in Aerospace Simulation Facilities, at the Polytechnic Institute of Brooklyn Graduate Center, 5-8 May 1969.

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DREV R-697/73 (UNCLASSIFIED)

CRDV, C.P. 880, Courcelette, Qué. - Conseil de recherches pour la défense

"Summary of Re-Entry Physics Research Program on Turbulent Wakes" par D. Heckman

Ce rapport comprend surtout un catalogue de plus de 100 documents, Rapports, Notes techniques et Mémorandums, publiés au CRDV au cours d'un programme de recherche sur les sillages turbulents des projectiles hypersoniques, programme exécuté conjointement par le CRDV et l'ARPA au Centre de recherches pour la défense, Valcartier. (N C)

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